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21a. NAME OF RESPONSIBLE INDIVIDUAL S. C. Tietsworth	21b. TELEPHONE (include Area Code) (619) 553-4199	21c. OFFICE SYMBOL Code 832

DETECTION OF ELECTRICAL CORONA ON LOW FREQUENCY RADIO TRANSMIT ANTENNA SYSTEMS

David G. Fern
Steven C. Tietsworth

Naval Ocean Systems Center
Code 832
San Diego, CA 92152-5000

ABSTRACT

Low frequency radio transmit antennas are used for a variety of applications in marine navigation and submarine communications. These systems are typically high power (50-1000 kW) physically large but electrically small with very high voltages (100-500 kV) present on some antenna elements. In many applications the limiting output power of the antenna system is determined by the onset of electrical corona which occurs on antenna elements where electric fields are very high. When corona occurs it is extremely damaging to antenna components and drains power from the transmitted signal. There are currently no practical systems available for detection of corona occurrence in low frequency transmit antenna systems. This paper discusses electrical corona phenomena, research work done on measurement of signal characteristics of corona onset, and the potential of utilizing frequency domain analysis of antenna current signals for corona onset detection.

BACKGROUND

Shore based low Frequency radio transmitting systems are used extensively to provide reliable communications to submerged submarines. Low frequencies (20-60 kHz) are used for this purpose as they lie in the only region of the electromagnetic spectrum (apart from a narrow region in the visible wavelengths and ELF frequencies below 100 Hz) where seawater is "transparent" enough to allow for communication with a submerged object. Nonetheless, the attenuation of the signal in seawater is still quite large. Transmitting systems must therefore operate at very high power levels to provide sufficient coverage. This high power requirement is the source of several problems in system design and operation, corona being one of them.

Antennas operating in this frequency range will be very small electrically, i.e., their largest dimension will be much less than one wavelength. Low frequency antennas are typically vertical monopole (tower) antennas ranging in height from 600 to 1500 feet. Even at the upper end of the LF portion of the spectrum, a 1500 foot antenna is less than one tenth of a wavelength long. These antennas are therefore very poor radiators of energy. The theory of electrically small antennas is well documented [1,2,3,4] and as such will not be outlined in detail. For the purposes of this report, it is sufficient to state that electrically small antennas can be represented as a small capacitance in series with a small resistance. This small capacitance yields a high capacitive reactance, resulting in a very high input impedance. If the current at the antenna feedpoint is I_a , the voltage at the feedpoint is given as

$$V_a = I_a X_a \quad (1)$$

where X_a is the capacitive reactance of the antenna. This voltage can be assumed to exist on the entire antenna structure as the frequency of operation is very low. This is equivalent to ignoring the inductance of the antenna which makes the antenna voltage increase with height.

The power radiated is given by

$$P_{rad} = I_a^2 R_r \quad (2)$$

where R_r is the radiation resistance of the antenna. The radiation resistance of the antenna is one component of the small resistance in series with the antenna capacitance (the other resistive component is the ohmic loss resistance). The radiation resistance is a function of the antenna's effective height, h_e and is given by

$$R_r = 160\pi^2 \left[\frac{h_e}{\lambda} \right]^2 \quad (3)$$

where λ is the wavelength. From this equation it is clear that the radiation resistance is proportional to the square of the ratio of the antenna height to the wavelength. This number is always quite small at low frequencies. From equation (2), to obtain a large radiated power, the antenna feedpoint current must be quite large. Antenna feedpoint currents frequently are as large as 1000 amperes for a 1 MW installation. This large current results in very high voltages on the antenna structure, frequently on the order of 250 kV. At these voltages corona discharge becomes a real possibility, particularly during rainy or humid weather.

Corona is a very undesirable phenomenon on low frequency antennas for several reasons. Corona discharges radiate considerable amounts of high frequency noise. This can interfere with radio operations on other frequencies. These discharges also produce considerable amounts of acoustic energy, which can cause excessive mechanical vibration of cables and insulating structures. Perhaps the most important aspect of corona is the effect it has on the antenna impedance. Corona discharges often envelope entire sections of antenna cables, creating a conducting sheath. This alters the capacitance of the conductor. If the corona on the antenna is severe, the capacitance of the antenna can be altered, detuning the antenna system. As low frequency antenna systems generally have very high Q factors (and thus a very small bandwidth) the antenna current (and consequently, the radiated power) decreases rapidly with changes in tuning away from resonance. Corona also dissipates a considerable amount of power. Because of this, corona discharge on an antenna increases its input resistance. The combination of capacitance change and resistance increase due to corona deals a double blow to antenna performance. The detuning effect of capacitance change reduces the antenna feedpoint current while the increase in resistance decreases the antenna efficiency. The efficiency of an antenna is given by

$$\eta = \frac{R_r}{R_r + R_l} \quad (4)$$

where R_r and R_l are the radiation resistance and loss resistance, respectively. Corona discharges increase the antenna loss resistance, while the detuning effectively decreases the radiation resistance. As is the case for many low frequency antennas, R_r and R_l are very close to being equal, resulting in antenna efficiencies around 50 percent in the absence of corona discharges. Corona can rapidly erode this performance.

THE EXPERIMENT

To attempt to find a suitable method for detecting corona on low frequency antennas in its very early stages, wires of various diameters were raised to very high potentials until corona discharges commenced. The frequency spectrum of the current flowing in the wire sample was monitored during the measurements. At the onset of corona, harmonics of the fundamental frequency appeared and increased in amplitude as the potential of the wire sample was increased further. The experiment was conducted utilizing a rather novel device for generating high RF voltages. This device is illustrated in figure 1. Power from a 100 kilowatt low frequency transmitter is transported down a 50Ω coaxial transmission line to a building which houses the tuning network for a low frequency antenna. This is a concrete structure lined on the inside with copper sheet. The antenna tuning inductors are located here, as well as the high voltage test cell equipment. This high voltage test cell forms the capacitive half of a series tuned resonant circuit consisting of the test cell and the tuning inductors for the antenna. Upon entering the tuning (or helix) house, the transmission line is terminated in a transformer. This transformer steps up the very low impedance of the series tuned test cell circuit to approximately 50Ω for maximum power transfer. When the circuit is tuned to resonance the high voltage test cell is at a potential much higher than the transmitter could deliver on its own.

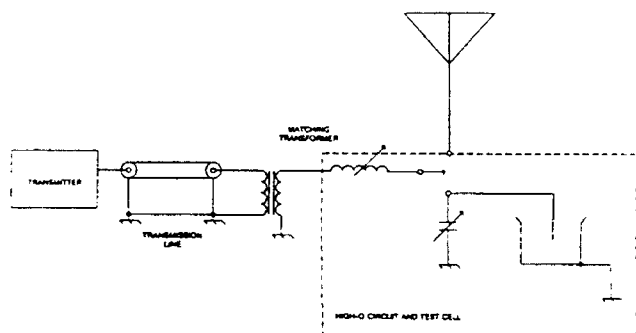


Figure 1 – Test Circuit

The high voltage test cell that was used for testing vertical wire samples is depicted in figure 2. The samples are connected between the two horizontal test plates. The top plate is then raised until the wire sample is held taut. The high voltage is applied at the top of the structure through the feedline. The ground side of the test cell is made of wire mesh supported by a PVC framework. The framework is equipped with corona rings at the upper rim to prevent charge buildup along the upper edge of the mesh. The entire structure is placed over a large metal sheet which sits on the concrete floor. The wire mesh is connected to the ground side of the tuned circuit by a 1 inch stranded copper conductor.

The data acquisition was accomplished utilizing time domain and frequency domain measurements. The time domain instrument was a LeCroy Model 9400A Digital Storage Oscilloscope, and the frequency domain instrument was a Hewlett Packard Model 3585A Spectrum Analyzer. A tunable filter was inserted to remove the large amplitude fundamental signal flowing in the test cell from the data acquisition equipment. These instruments were connected to a Pearson current transformer connected in the ground return lead of the test cell. The Pearson transformer is a broadband pulse transformer with a cutoff frequency of approximately 2.5 MHz. The time waveform of the test cell current was displayed by the digital scope. A block diagram of the data acquisition setup used appears in figure 3.

Two different types of wire were used for this experiment. Stranded AWG #8 and solid AWG #18 wire were mounted in the test cell and driven well into corona at several different frequencies. The corona onset voltage of the two different wires is significantly different, as is expected from theory. The

corona process is initiated by the existence of an electric field sufficiently intense to strip electrons off of air molecules and accelerate them so that an avalanche of electrons is created by secondary collisions. This field intensity is a function of many factors, air pressure, chemical composition, temperature, humidity, etc. However, for two wires at identical voltage with respect to ground, the thinner wire has a higher electric field intensity at the surface, thus the critical field intensity required for corona onset is reached at a lower voltage for a thin wire than for a fat wire. These corona onset voltages have a weak frequency dependence which is in agreement with data obtained by Reukema [5] where the breakdown voltage of a sphere gap was observed to decrease with increasing frequency.

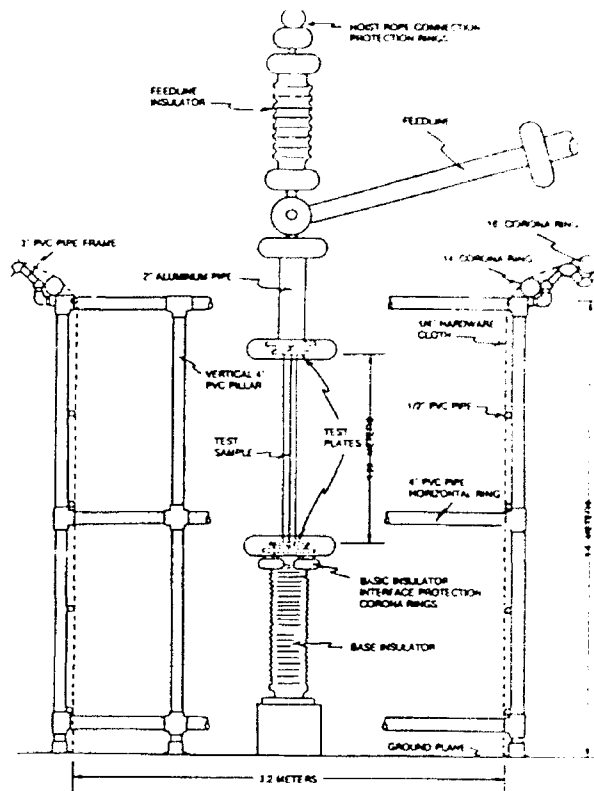


Figure 2 — High Voltage Test Cell

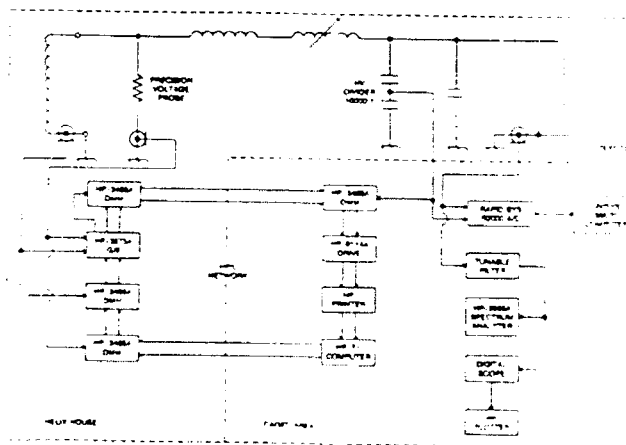


Figure 3 – Instrumentation Block Diagram

Two separate sets of measurements were performed. In one set of measurements, the current flowing in the high voltage test cell was measured and the spectrum displayed. In the other measurement, the current in the transformer secondary winding was measured. The significant difference in the visible spectrum provided a great deal of insight into the actual implementation of a corona detection system at an actual antenna site. As is apparent from the photographs of the corona spectrum on the test cell current and the transformer current, the transformer current shows far less harmonic content than the test cell current (see figures below). This is due to the filtering properties of the tuned circuit.

PRESENTATION OF DATA

This study generated a great deal of data, and this report shows a small subset of all that data. Figure 4 is a series of spectrum analyzer photos showing the spectrum of the current flowing in the high voltage test cell. In the first picture, the wire sample is at a potential of 40 kV and no corona discharges are present. The current spectrum is relatively pure. The large spike at the left end of the trace is the fundamental signal at 47.15 kHz. The vertical divisions are 10 dB each. The next picture shows the spectrum with the sample at 47 kV, right at the onset of corona discharge. Harmonic energy has appeared at three points. These points are the second, third, and fourth harmonics of the fundamental signal. The two remaining pictures show the spectrum as the sample is driven further and further into corona. There is a distinct series of harmonics present. The appearance of these harmonics is very abrupt at corona onset and as such provides a very clear indicator of corona. These harmonics appear long before the corona can be seen visually.

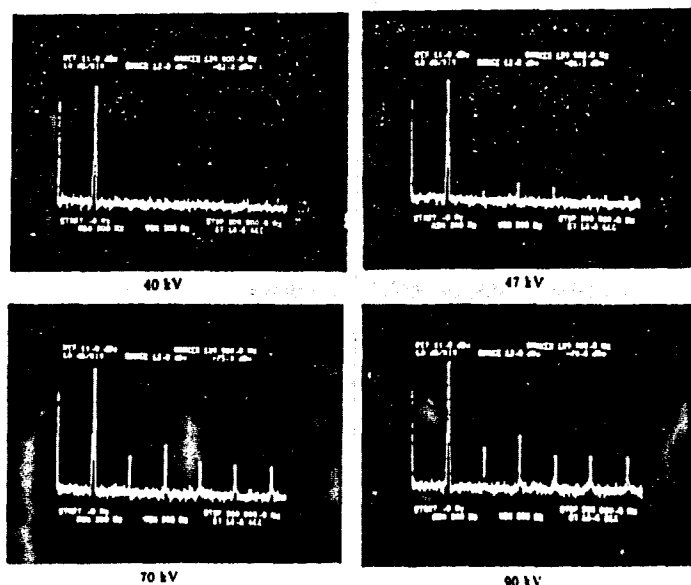


Figure 4 - Test Cell Current Spectrum: 47.15 kHz

Figure 5 is a spectral display of the current flowing in the secondary winding of the transformer. These measurements were made because in a practical implementation of a corona detector, the sensors will not necessarily be placed at the ends of the tophat radials where corona is directly occurring. If measurements are to be made at the base of a tall antenna, the spectrum of the antenna current might be different than the spectrum of the current at the corona discharge site. The figure shows that this is indeed the case. The first picture once again shows the current with the wire sample at 40 kV with no corona discharge. At corona onset in the second picture (47 kV), there still is no visible harmonic content in the transformer current. The last two pictures show that as the voltage on the wire sample is increased harmonic energy does begin to appear on the transformer current, but it is of much

lower amplitude than that of the test cell current. The reason for this is that the capacitance between the test cell and the transformer secondary winding acts as a filter for the high frequency harmonics being generated by the corona in the test cell. Most of the high frequency energy is current which circulates in the test cell without flowing elsewhere in the circuit. Only at very high levels of corona is there sufficient harmonic energy to permit detection outside of the region of corona discharge. This fact shows that for early corona detection, the corona sensors need to be placed very close to the sites where corona is expected to occur.

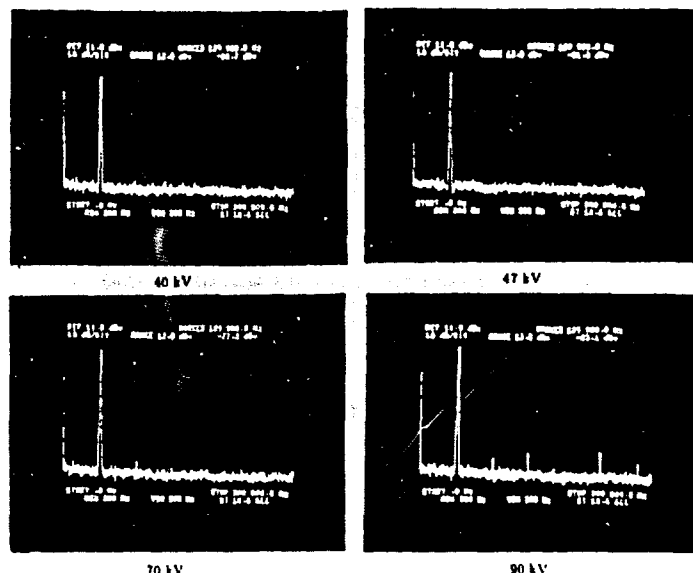


Figure 5 - Transformer Current Spectrum: 47.15 kHz

Figure 6 is a time domain plot of the test cell current and test cell voltage of the case shown in figure 4. Channel 1 is the current in the test cell, and channel 2 is the voltage in the test cell. The figure is for 40 kV with no corona. The voltage and current signals are sinusoidal, with no harmonic energy present. Figure 7 is the time domain plot for the 90 kV configuration. Notice that the voltage signal is still uncorrupted, however the current signal shows high frequency spikes on the positive going portions of the sinusoids. This is the corona energy. It is apparent that the corona current flows at the same point in the cycle, and as such, is not a steady phenomenon, but a pulsed phenomenon. The voltage on the test cell is uncorrupted. The corona discharge does not appreciably load down the transmitter supplying the test cell with energy. As such, the corona occurs without distorting the voltage applied to the test cell. The frequency domain plots are

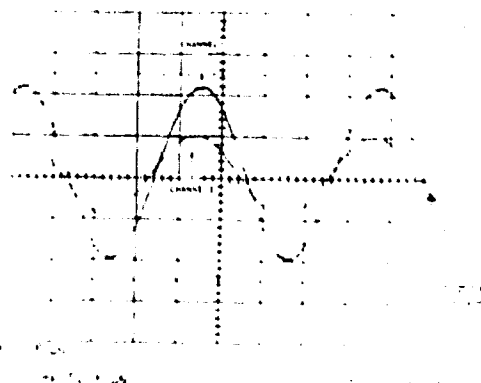


Figure 6 - Test Cell Time Plot No Corona 47.15 kHz

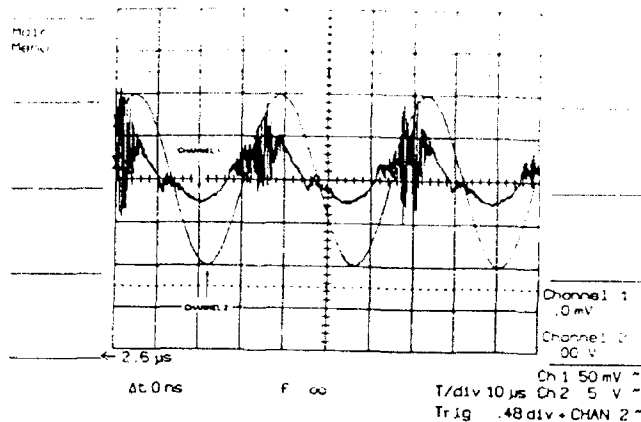


Figure 7 - Test Cell Time Plot: Corona: 47.15 kHz

far more revealing and as such, it is clear that frequency domain measurements are superior to time domain measurements. No time domain plots are shown for the transformer secondary current of figure 5 as there is no visible harmonic content in the current signal.

CONCLUSIONS

This research revealed a reliable method for corona detection on operational low frequency transmitting antennas. The method utilizes the fact that a corona discharge will excite harmonics of the fundamental frequency being applied to the antenna as shown in the frequency domain plots. It was demonstrated that shunt capacitance between the corona discharge site and the sensor position will make detection of corona very difficult if the sensors are placed outside of the corona region. This suggests that sensors with very high dynamic ranges will be required if it proves necessary to place corona sensors some distance from the suspected corona sites. The actual dynamic range requirements would depend on detector installation, which has not been investigated here.

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